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REACTIVITY CONTROL OF FAST-SPECTRUM REACTORS BY REVERSIBLE HYDRIDING OF YTTRIUM ZONES

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ABSTRACT

The temperature-dependent equilibrium hydrogen content of yttrium hydride above 1173^{O} K is investigated as a means of reactivity control for a cylindrical reactor using zones of hydride in various in-core and reflector configurations. The temperature dependence is such that the control system is inherently self-regulating. Severe power peaking, dependent on the hydrogen density, occurs at the hydride-core interfaces. Use of auxiliary control for startup reduces the control demand on the variable hydriding system and thus reduces the power peaking. A configuration for which the reactivity control satisfies required core life and power peaking limits is presented.

STAR Category 22

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SUMMARY

Reactivity control is examined for long-lived fast-spectrum nuclear reactors containing yttrium hydride moderating zones. Temperature variation of the hydride provides attendant reversible changes in the equilibrium concentration of hydrogen which in turn control the reactivity. Storage of released hydrogen in a reservoir permits reversible hydriding to occur. The temperature dependence of the hydriding is such that this control concept is inherently self-regulating.

Several metal hydrides that are fabricable have high hydrogen concentrations which are temperature dependent. For high-temperature fast-spectrum reactors, yttrium hydride is especially attractive because its temperature dependent reversible hydriding range begins at about 1173° K, almost 200° K higher than for other metal hydrides.

Reactivity dependence on hydride temperature and associated equilibrium hydrogen concentration is calculated for several cylindrical core-hydride configurations. Desired control swing for the long-lived reactor control system is about 10.5 percent reactivity.

The possible variation of hydrogen concentration within yttrium hydride does not provide full control for an annular hydride reflector zone or for an in-core hydride disk. Seeding of the hydride reflector with small amounts of fuel provides additional control swing. However, power peaking at the core-hydride interfaces is severe in these cases.

The configuration offering the most control swing consists of an annular core bounded internally by a central hydride rod and externally by an annulus of hydride. However, peak- to average-power ratios of 1.59 (hydride-rod - annular-core interface) and 2.30 (annular-core - annular-hydride interface) occur. The power peaks may be reduced by reducing the control swing required of the reversible hydriding system. This is done by allowing the reactivity needed for reactor startup and temperature defect to be controlled by an auxiliary system, such as a removable thermal poison sheath around the central hydride rod.

INTRODUCTION

Nuclear reactors, because of their potentially high total power output, appear especially attractive as space power sources. For manned missions, or those involving radiation-sensitive electronics or payload, shielding must be provided. Smaller reactors require lower shield weights so that compact fast-spectrum reactors warrant investigation.

A reactivity control system is needed for operation of a nuclear reactor throughout its lifetime. Coarse reactivity control must be available for startup and shutdown. More sensitive control measures are needed, however, to maintain fixed power levels in the reactor during its life. Further requirements are that a control mechanism be failsafe and that it afford overall operating stability to the reactor.

Although a fast reactor does not require a moderator, a variably moderating reflector or in-core zone, could serve as a spectral control region. Conceivably, the region could provide full control, partial control, or just an enhanced negative temperature coefficient. The introduction of such a zone into or around a fast-spectrum reactor partially moderates some of the high-energy neutrons to thermal energies. At thermal energies, the fission cross sections are considerably larger and, if parasitic capture of core materials has not increased proportionally, the multiplication factor k_{eff} should increase. However, the degree of moderation must be limited if the overall mixed spectrum is to remain essentially fast. Consequently, by controlling the moderator composition, the spectrum and k_{eff} may be controlled. On a unit volume basis, hydrogen is the best material for slowing down neutrons. Certain fabricable metal hydrides have hydrogen concentrations comparable to that of water. Furthermore, the equilibrium hydrogen concentrations in the hydrides of titanium (TiH_x), zirconium (ZrH_x), and yttrium (YH_x) show a marked temperature dependence (ref. 1). The stoichiometric ratios x of the hydrides are monotonically decreasing functions of temperature, within specified ranges.

Reversible hydriding can change moderator properties by diffusive removal or addition of hydrogen to the moderator as its temperature is changed. This property suggests that, by controlling the temperature of a metal hydride zone and providing a hydrogen reservoir, the hydrogen concentration and therefore k_{eff} may be controlled. This hydriding is reversible, and thus moderator properties can be reversibly changed by diffusive removal or addition of hydrogen. Such a control concept is inherently safe because a loss of hydrogen from the hydride will decrease k_{eff}. The control concept is also self-regulating since the hydrogen concentration in the hydride and the resultant k_{eff} decrease as the reflector temperature increases. This self-regulating property will tend to offset depletion of the fuel.

The inherent stability of this hydride control concept has been demonstrated by a thermal reactor critical assembly using zirconium hydride as a distributed in-core mod-

erator (ref. 2). The assembly maintained equilibrium conditions overnight without any operator initiated action. The ZrH_x in-core moderator and the ZrH_x donor assemblies were independently heated electrically.

The transient response of a zirconium hydride controlled thermal reactor was also investigated in reference 2. A step insertion of 0.032 percent reactivity was made. The resulting transient reached a peak in about 3 minutes, and a new equilibrium power level, 9 percent higher, was attained in about 7 minutes.

More extensive analytical and experimental work has been done on the mobility of hydrogen in porous zirconium and porous zirconium-uranium alloy (ref. 3). The porous material consisted of particles about 0.0076 centimeter in diameter. The response time for a hydrogen concentration change in a 1.27-centimeter-thick slab, 80 percent dense, driven by a step change in the pressure on the surface, should be less than 1 second.

The hydriding method of reactivity control has been considered for relatively low temperature thermal reactors. The TURPS thermal reactor concept (ref. 4) uses ZrH_x as an in-core distributed moderator. A patent for the concept of reactor control by hydrogen diffusion has been issued to R. Magladry of the Martin-Marietta Corporation (ref. 5). However, because of the low hydrogen content of ZrH_x at high fast-reactor temperatures, a sufficiently high hydrogen concentration would require a large equilibrium hydrogen pressure. Thus, for high-temperature fast-spectrum reactors, the containment of ZrH_x would be difficult, if not impossible.

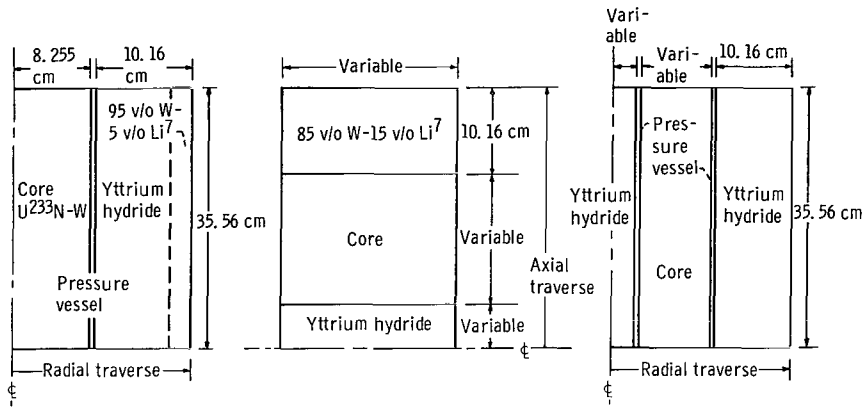
Yttrium hydride, though, holds some promise for fast reactors since the variation of its hydrogen content occurs at temperatures above 1173° K, about 200° K higher than for other hydrides. However, even this temperature capability may not be sufficient for YH_x to be feasible as an in-core distributed moderator.

For the present study, it is assumed that the temperature of zones of YH_x can be regulated within the variable hydrogen temperature-dependent range. The results of the calculations determine the reactivity control and power profiles for three cylindrical fast cores containing zones of yttrium hydride. An examination of the results of these three configurations provides sufficient neutronic information to determine the characteristics of the hydride control concept.

DESCRIPTION OF REACTOR CORE AND REFLECTOR

The first configuration considered is a cylindrical core with annular YH_x reflector. This configuration serves as the basic case from which other configurations were formulated.

Each configuration is subject to the same total core fuel loading. The basic core is a right circular cylinder with a diameter of 16.51 centimeters (6.5 in.) and a length of



(a) Basic with yttrium hydride annulus.

(b) Split axial with yttrium hydride central disk.

(c) Central rod with yttrium hydride central rod and annulus.

Figure 1. - Schematic drawings of core-reflector configurations.

TABLE I. - MATERIAL DESCRIPTION AND ATOM DENSITIES

Component	Description		Nuclide	Atom density, atoms/b-m
	Material	Volume percent		
Core	Natural tungsten clad	3.25	W	-------
	Lithium 7 coolant	10.25	Li^7	0.3864
	Fuel matrix	86.50		
	Uranium 233 nitride fuel	45	U^{233}	1.2806
			N	1.2806
	Tungsten support	25	W	[a]1.5720
	Void	30	----	-------
Radial reflector	Lithium 7	5	Li^7	0.1885
	Natural tungsten	95	W	6.004
Axial reflector	Lithium 7	15	Li^7	0.5655
	Natural tungsten	85	W	5.372
Pressure vessels	Natural tantalum	0.0123	Ta^{180}	0.0006802
		99.9877	Ta^{181}	5.52932
	Natural molybdenum	-------	Mo	6.4
Thermal poison control sheath	Boron 10 carbide ($B_4^{10}C$)	-------	B^{10}	11.64
			C	2.91

Component	Description			Nuclide	Atom density, atoms/b-m
	Material	Stoichiometric ratio, x	Temperature, ^oK		
Control reflector	Yttrium hydride, YH_x	All	----	Y	2.75
		2	1173	H	5.5
		1.2	1573	H	3.3
		.727	1623	H	2.0
		.5	1673	H	1.375

[a]Includes all tungsten in core.

35.56 centimeters (14 in.). The fuel is uranium 233 nitride ($U^{233}N$), the coolant is lithium 7 (Li^7) and the cladding is natural tungsten (W). A schematic drawing of the basic radial configuration showing the cylindrical core, annular pressure vessel, and an annular reflector is given in figure 1(a).

A split axial configuration, which consists of an yttrium hydride in-core disk sandwiched between two half-cores, is also studied. This reactor is reflected axially at each end by tungsten (fig. 1(b)).

A third configuration uses a central rod and an annulus of YH_x in order to expose more fuel surface to the moderating action of the hydride (fig. 1(c)).

Pressure vessels of 0.4 and 0.9525 centimeter thickness are used. The pressure vessel materials considered are tantalum (Ta) and molybdenum (Mo), but other materials with sufficiently high melting points could also be used. Yttrium hydride and tungsten are used for reflectors.

The core, pressure vessel, and reflector compositions are given in table I. The configurations are discussed in more detail in the section DISCUSSION AND RESULTS.

DESCRIPTION OF CONTROL SYSTEM

Yttrium Hydride Characteristics

The metal hydrides of titanium (TiH_x), zirconium (ZrH_x), and yttrium (YH_x) have large equilibrium hydrogen concentrations which are strongly temperature dependent. This characteristic suggests their use in a reflector or moderator reactivity control system.

Yttrium hydride, however, is most attractive for high-temperature reactors because it offers a hydrogen containment capability about 200° K above TiH_x or ZrH_x (fig. 2) and thus will require less cooling. The useful temperature range available for YH_x is from 1173° to about 1673° K (ref. 1). Below 1173° K, the hydrogen content of YH_x is constant at $N_H = 5.5$ atoms per barn-meter and a stoichiometric ratio $x = 2$, where $x = N_H/N_Y$ and N_Y is the atom concentration of yttrium in YH_x. Figure 3 (ref. 6) indicates that $x = 0.5$ is a lower limit at conveniently attainable low pressures, thus an extrapolation of the data of reference 1 (fig. 2) is performed to the value of $N_H = 1.375$. This extrapolation which assigns 1673° K to this density is somewhat arbitrary. However, the reactivity control available depends, to first order, only on the hydrogen concentration variation, whatever the associated temperature may be. The concentration thus ranges between $N_H = 5.5$ and $N_H = 1.375$ for a constant yttrium nuclear density of $N_Y = 2.75$. Appendix A delineates the general characteristics of these metal hydrides that make them desirable for space nuclear power systems.

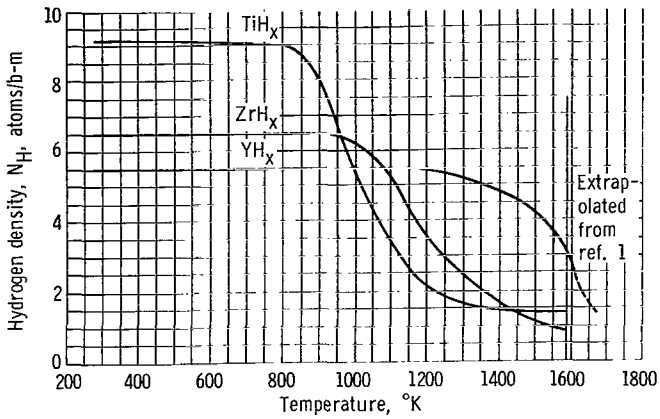


Figure 2. - Content of absorbed hydrogen in certain metal hydrides in equilibrium with 15 psia (1.034×10^5 N/m^2) hydrogen (ref. 1).

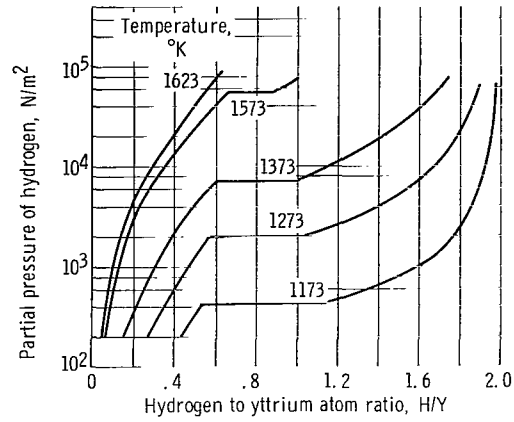


Figure 3. - Isothermal curves of equilibrium partial pressure of yttrium-hydrogen system (ref. 5).

Yttrium Hydride Control Concept

The reactivity control of a fast-spectrum reactor by a differential hydrogen moderating zone requires that the hydrogen concentration be varied. This reversible hydriding concept utilizes distinct temperature-controlled YH_x moderator regions connected to a hydrogen reservoir. The hydrogen concentration in the hydride is varied by movement of hydrogen between the YH_x region and the reservoir. The core may be required to operate at temperatures several hundred degrees above the range in which the desired hydrogen concentrations in YH_x are to be maintained, consequently it may be necessary to cool the YH_x region below the core temperature.

The equilibrium hydrogen concentrations in figure 2 are obtained for a constant pressure of 1.034×10^5 newtons per square meter absolute (15 psia). A mechanism for maintaining a constant pressure must be considered as part of a more detailed control system design.

Reactivity control is obtained by varying the temperature and, consequently, the equilibrium hydrogen content of the YH_x region. Regulation of the YH_x region coolant flow, independent of the core coolant flow, may provide the temperature variation needed for reactivity control. However, the following description of the control process is independent of how the YH_x temperature is changed.

If the temperature of the hydride increases, whether in response to a core power perturbation or to an operator command, hydrogen will be transferred from the YH_x region into the reservoir. The core, being less moderated, loses reactivity, which causes the core power and temperature to level off. Similarly, a drop in YH_x temperature allows hydrogen to enter the YH_x region from the reservoir, increasing moderator hydrogen concentration thereby increasing reactivity.

Since such a concept relies on the presence of hydrogen in the moderator zone to maintain criticality, a loss of hydrogen from the moderator will shut down the reactor. This self-regulating property will tend to offset the burnup of the fuel by continuously supplying more hydrogen to the reflector as the fuel is depleted provided that the average YH_x temperature is appropriately reduced.

Representative Control Sequence

The startup-operation-shutdown sequence may be illustrated with reference to figure 4. This sequence supposes that hydriding is the only control method.

(1) Prior to startup, both the core and pure yttrium reflector are at 300° K (point 1).

(2) The yttrium, which is inside a plenum, is heated to 1673° K by an external heat source. This will result in little change in the subcritical state of the core.

(3) Hydrogen from the reservoir is transferred to the pure yttrium reflector until it saturates at 1673° K, $N_H = 1.375$ (point 2 to point 3). Stability of the yttrium-hydrogen system requires that sufficient hydrogen be available to maintain saturation of the YH_x region. By independently controlling the yttrium temperature and the hydrogen overpressure, all subsequent hydrogen-concentration - temperature states can be made to lie on the curve in figure 4. As the hydrogen is being absorbed by the yttrium, the core multiplication factor k_{eff} increases.

(4) Lowering the temperature of the YH_x region increases the hydrogen content (point 3 to point 4). In the meantime, k_{eff} continues to increase, reaching criticality at

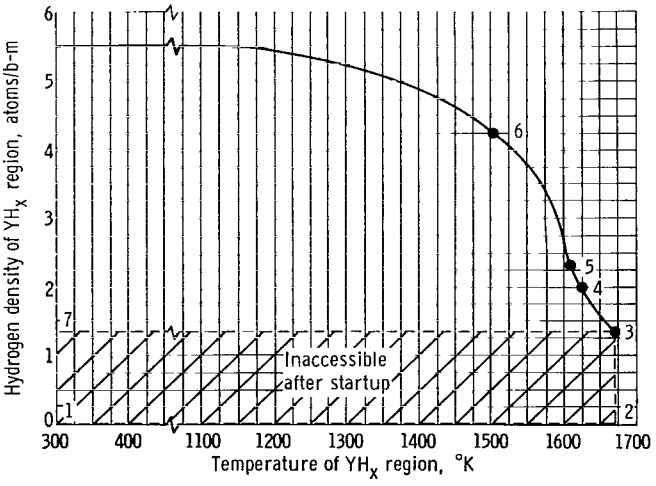


Figure 4. - Profile of hydrogen-concentration - temperature states of yttrium hydride region during reactor operation. Configuration: basic core; no pressure vessel; 10.16-centimeter yttrium hydride annular reflector.

point 4. The location of 4 is determined by the neutronic characteristics of the reactor configuration.

(5) The core may be brought to power by lowering the YH_x temperature slightly. At the operating power level, the YH_x temperature at point 5, allows for a representative temperature defect of 1 percent.

(6) As fuel depletion and fission product buildup reduce the excess reactivity over the lifetime of the reactor, the hot critical point, point 5, must gradually shift up the curve to point 6, since more hydrogen will be necessary to maintain criticality. The location of point 6 in the figure corresponds to a representative value of fuel burnup of 4 percent. This burnup value of 4 percent was obtained from depletion studies performed on similar reactors using the VULCAN depletion program (ref. 7).

(7) Shutdown requires that the YH_x region be heated above the temperature corresponding to the critical point, point 5, to point 3 where $N_H = 1.375$ represents the minimum equilibrium hydrogen concentration now attainable. When the core is shutdown, the YH_x region may then be cooled to 300° K (point 3 to point 7). During this step, the hydride zone must be isolated from the hydrogen reservoir so that the concentration of hydrogen remains at $N_H = 1.375$.

(8) Restart will follow points 7 to 3 to 4 to 5 in a manner similar to startup.

However, if auxiliary control devices, such as a conventional movable control rod, are also incorporated into the system, the minimum hydrogen concentration may be the initial hot critical condition. In this case points 3, 4, and 5 will coincide.

CALCULATIONAL PROCEDURE

To determine the reactivity control available from a system, the multiplication factors k_{eff} of that system under various conditions are determined. The calculations of k_{eff} were performed with digital computer programs. Atom densities for the homogenized regions are given in table I. The GAM-II and GATHER-II programs (refs. 8 and 9) were used with the listed atom densities to obtain multigroup cross sections for the various regions. All atom densities correspond to room temperature except those of lithium 7 and hydrogen. The lithium 7 density was not varied over the temperature range 1173° to 1673° K, but it was fixed at an average value attained at 1373° K. The yttrium hydride cross sections were obtained from the GAM-II program using the hydrogen density at 1373° K. Thermal (low energy) cross sections were calculated for the YH_x region at each temperature using the GATHER-II program. A hydrogen gas kernel was generated at each temperature for the corresponding hydrogen densities from figure 2.

The structure of the 18 energy groups used (13 fast and 5 thermal) is given in table II. The spatial calculations were performed with the S_4-P_0 transport approximation

TABLE II. - ENERGY GROUP STRUCTURE

(a) GAM - fast

Group number	High lethargy boundary[a]	Reduced group number
1	1.0	1
2	1.5	
3	2.0	
4	2.5	
5	3.0	2
6	3.5	
7	4.0	
8	4.5	
9	5.5	
10	6.5	
11	7.5	
12	9.5	3
13	17.0	4

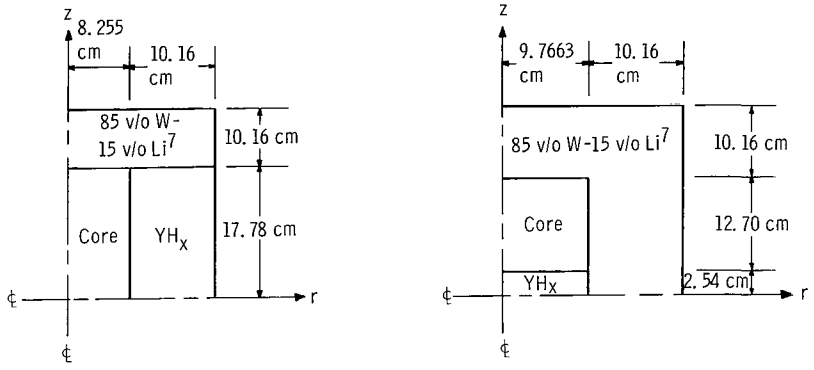
(b) GATHER - thermal

Group number	Low lethargy boundary	Reduced group number
14	17.0	5
15	17.504	
16	17.951	
17	18.644	6
18	20.030	

[a]The lethargy u corresponding to an energy E is given by $u = \ln (10 \text{ MeV})/E$. The lower lethargy boundary of group 1 is $u = -0.4$.

(second method in reference) in one dimension using the TDSN transport theory program (ref. 10). The mesh structure of the model is tailored to provide relatively more spatial detail at the YH_x interfaces. In the one-dimensional spatial calculations, a total axial and total radial reflector savings, each of 9.0 centimeters, is maintained for all configurations and temperatures.

This survey was performed with one-dimensional (1-D) calculations. However, a two-dimensional (2-D) cylindrical calculation was performed for a basic radial and a basic split axial configuration. The 2-D geometric configurations are shown in figures 5(a) and (b).



(a) Single core, hydride annulus.

(b) Split axial core, hydride disk.

Figure 5. - Calculational segments of two-dimensional cylindrical configurations.

The 2-D radial configuration used no radial reflector other than YH_x although the 1-D calculations examined the effect of a 95 volume percent tungsten - 5 volume percent lithium 7 radial reflector (referred to as 95 W). The 2-D radial configuration is reflected axially at each end by a mixture of 85 volume percent tungsten - 15 volume percent lithium 7 (referred to as 85 W). The 2-D split axial configuration is reflected both radially and axially by 85 W. The larger coolant fraction in the axial reflectors results from the greater coolant volume needed by the inlet plenum.

Computer storage limitations forced a reduction from 18 to 6 energy groups for the 2-D calculation (table II). Equivalent 1-D radial and axial calculations with reduced group structure were performed for comparison with the reduced group 2-D configurations. All multiplication factors and reactivities quoted are normalized to the equivalent 18 group 2-D values.

The reactivity control swing in percent is defined as

$$\frac{k_{eff}^{1173} - k_{eff}^{1673}}{k_{eff}^{1173}} 100$$

(referred to as $\Delta k/k$ in the figures), where k_{eff} is the multiplication factor at the YH_x region temperature (^{O}K) indicated by the superscripts. Ratios of peak to average power $P_{max}/\bar{P}$ are obtained from 1-D calculations using fission rates extrapolated to the core surface.

DISCUSSION AND RESULTS

Annular Reflector

The simplest reflector region considered is an annulus of hydride around a cylindrical core. This configuration is used to determine the general characteristics of the control concept, to set forth a normalization procedure applicable to all configurations, and to examine the effect of varying the initial specifications.

For the basic cylindrical core with no pressure vessel and with a 10.16-centimeter YH_x annulus, the multiplication factor k_{eff} was obtained as a function of temperature. The results are given in figure 6, and the temperature-dependent range of the hydrogen

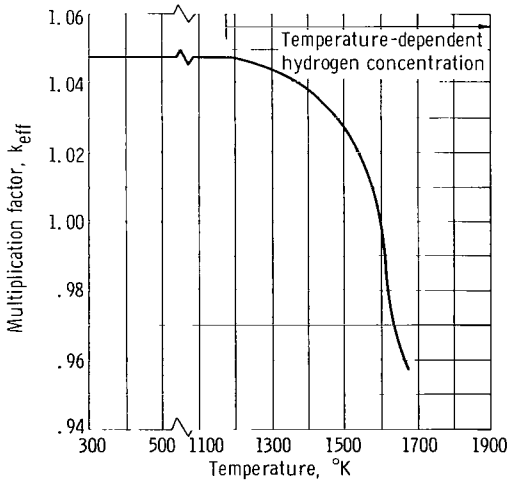


Figure 6. - Dependence of multiplication factor on yttrium hydride region temperature. Configuration: basic core; no pressure vessel; 10.16-centimeter yttrium hydride annular reflector.

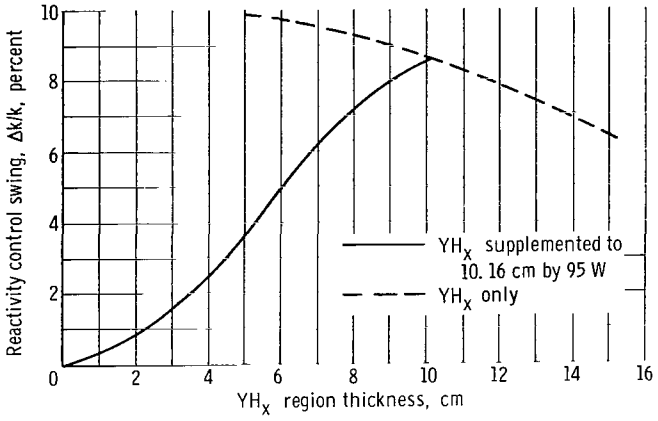


Figure 7. - Reactivity control swing at various yttrium hydride reflector thicknesses. Configuration: basic core; no pressure vessel; variable annular reflector.

is identified. The curve indicates a smooth variation of k_{eff} with YH_x temperature over its full useful range, a desirable characteristic for control purposes. The reactivity control swing between the temperatures of 1173° and 1673° K was then determined for several annular reflector arrangements.

The solid curve in figure 7 shows the control swing in percent as a function of YH_x region thickness when supplemented to 10.16 centimeters by 95 W. The dashed curve in figure 7 is the control swing as a function of the thickness of a YH_x reflector with no supplemental tungsten. The dropoff in the dashed curve above 5 centimeters thickness is a result of the reactivity worth per unit reflector thickness becoming increasingly smaller for the high hydrogen density (1173° K) than for the low density (1673° K).

For the 10.16-centimeter YH_x reflector, the thermal power is 15 percent of the total power when the YH_x temperature is 1173° K (N_H = 5.5 atom/b-m) and is 2.6 percent of the total when the YH_x temperature is 1673° K (N_H = 1.375 atom/b-m). Also a higher k_{eff} is obtained at 1173° K than at 1673° K thus indicating that the control swing of 8.5 percent is provided by thermal neutrons.

Normalization procedure. - Since the initial fuel loading chosen for this concept is too low, normalization to more appropriate multiplication is made. The normalization procedure is described for the basic radial configuration (annular reflector). The purpose is not to establish a design fuel loading but merely to demonstrate the method of obtaining such a fuel loading.

Figure 8 shows the basic radial configuration k_{eff} as a function of the N_H of the YH_x region. The solid curve indicates that the 86.5 volume percent fuel matrix containing 45 volume percent fuel, 30 volume percent void, and 25 volume percent tungsten has a k_{eff} of about 0.96 at the minimum hydrogen density. However, it is only necessary to

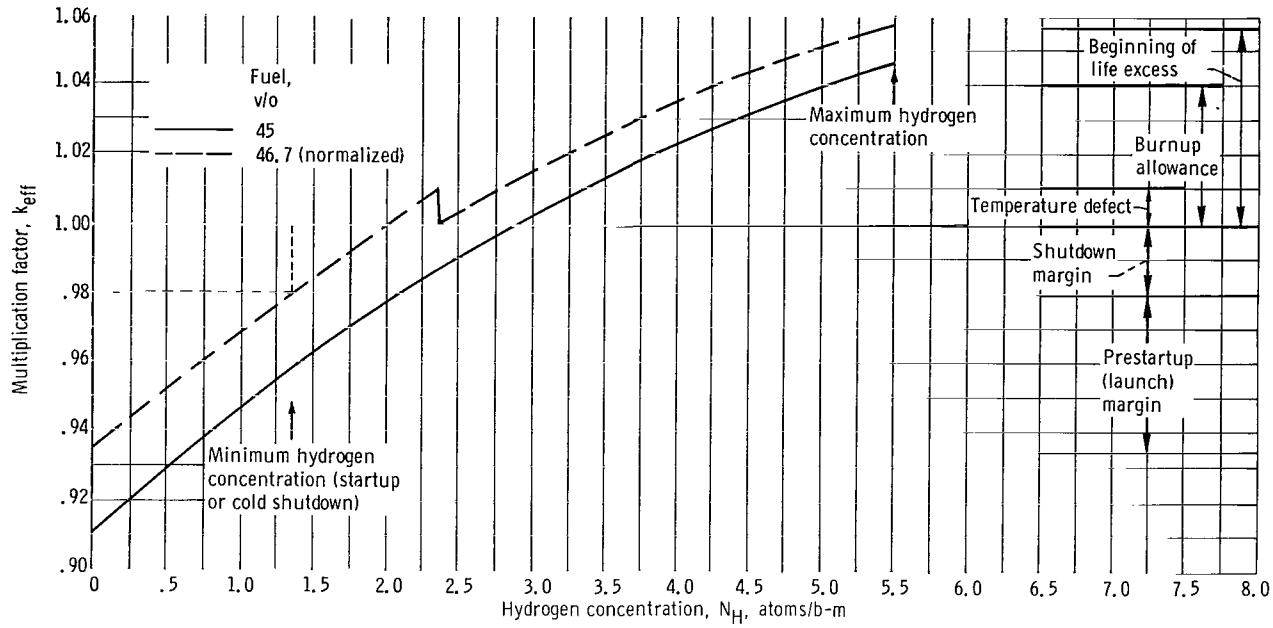


Figure 8. - Basic core multiplication factor as function of hydrogen concentration in yttrium hydride region. Configuration: basic core; no pressure vessel; 10.16-centimeter yttrium hydride reflector.

have the core about 2 percent subcritical (k_{eff} = 0.98) when the minimum hydrogen condition is achieved.

The effect of varying the fuel and void fractions within the 86.5 volume percent fuel matrix was considered. Figure 9 shows an almost linear dependence of k_{eff} on fuel loading between 45 and 51 volume percent fuel. From this figure, a new fuel loading of 46.7 volume percent fuel, 28.3 volume percent void, and 25 volume percent tungsten is obtained which yields the dashed (neutronics normalized) curve of figure 8. The break in this curve at k_{eff} = 1.0 reflects an assumed temperature defect of 1 percent.

This loading provides a shutdown margin, from critical hydrogen concentration, of 2 percent. Cold criticality for the 46.7 volume percent fuel loading, is now achieved at N_H = 2.0, which initially fixes point 4 of figure 4 at 1625° K. Hot criticality then occurs at N_H = 2.35, which establishes point 5 of figure 4 at 1610° K.

Extrapolation of depletion studies of similar reactors, using the VULCAN program (ref. 7), provides a burnup of 4 percent for a representative life of 20 000 hours at 1.0 megawatt. Consequently, the end of life (point 6) on the curve in figure 4 is set at N_H = 4.20 (1505° K) corresponding to k_{eff} = 1.04 (dashed curve, fig. 8). All normalization implicitly assumes the separability of radial and axial fluxes and that isolated k_{eff} changes are additive.

Power profile. - The radial power profile of the basic core with no pressure vessel shows considerable peaking at the core - YH_x-reflector interface. The ratio of radial peak

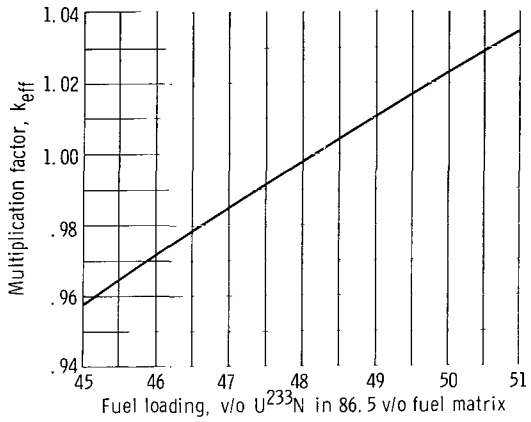


Figure 9. - Basic core multiplication factor dependence on core fuel loading. Tungsten loading constant at 25 volume percent of 86.5 volume percent fuel matrix. Minimum hydrogen in reflector, 1.375 atoms per barn-meter.

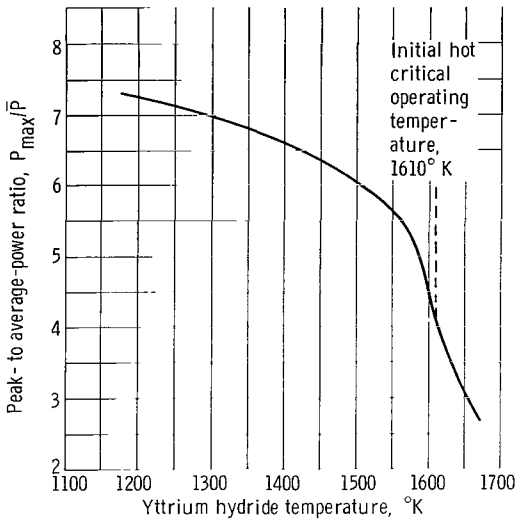


Figure 10. - Peak- to average-power ratio in core as function of annular yttrium hydride region temperature. No pressure vessel.

to average power in the undepleted core varies with YH_x region temperature from 7.3 at 1173° K to 2.7 at 1673° K (fig. 10). This power peaking is primarily caused by thermal neutrons, as evidenced by the fact that the thermal power fraction is 0.15 at 1173° K and only 0.026 at 1673° K. With no other control, in order to initiate a hot critical condition in the reactor, the YH_x temperature must be lowered to 1610° K, as indicated in figure 4.

The radial power ratio, $P_{max}/\bar{P} = 4.1$, at this temperature, 1610° K, is considered the largest attained during the reactor lifetime. Although the hydrogen concentration in the reflector will continue to increase toward the end of life, the fuel depletion and especially the relatively higher depletion at the interface is considered sufficient to prevent $P_{max}/\bar{P}$ from increasing. Table III contains the ratios $P_{max}/\bar{P}$ of several reactor variations at 1173°, 1610°, and 1673° K. The values at 1610° K are obtained by scaling the value at 1673° K according to the curve in figure 10.

Effect of design specifications. - Modifications of the basic radial configuration and their individual effects on power profile and control swing are described in the following sections.

Core dimension: The effectiveness of the hydride control concept depends on the surface area of the core that is exposed to the hydride. The surface to volume ratio for a radially reflected cylinder is proportional to the reciprocal radius of the core. The effect of changing the length to diameter ratio (L/D) from 2.15 to values of 1.16 and 0.59 was investigated. The control swing for the 10.16-centimeter YH_x reflector for the full temperature change was determined as the L/D ratio of the core was decreased, with core volume held constant (table IV). The flattening of the core decreases the reactivity

TABLE III. - PEAK- TO AVERAGE-POWER RATIOS

Description of configuration			Interface	Peak- to average-power ratios,[a] $P_{max}/\overline{P}$		
Core	Reflector	Pressure vessel		Temperature, ^{o}K		
				1173	1610 (b)	1673
Basic cylindrical, 8.255-cm radius	10.16-cm yttrium hydride annular	None	Core - Yttrium hydride reflector	7.31	4.10	2.66
		0.40-cm molybdenum		6.09	3.43	2.24
		0.9525-cm molybdenum		4.76	2.74	1.83
		0.9525-cm tantalum		1.78	----	----
Split axial, two 12.70-cm-thick half cores separated by 2.0-cm-thick yttrium hydride disk	10.16-cm tungsten axial	None	Yttrium hydride - Core	10.82	----	2.30
	10.16-cm yttrium hydride axial	0.9525-cm molybdenum	Central: Yttrium hydride - Core	5.76	----	1.75
			End: Core - Yttrium hydride	1.30	----	.83
4.0-cm-diameter central yttrium hydride rod, 6.597-cm-thick annular core	10.16-cm yttrium hydride annulus	0.40-cm molybdenum	Yttrium hydride rod - Core	2.30	1.59	1.27
			Core - Yttrium hydride annulus	3.66	2.30	1.69
	2.34-cm yttrium hydride annulus 7.62-cm molybdenum annulus	0.40-cm molybdenum	Yttrium hydride rod - Core	2.59	1.72	1.33
			Core - Yttrium hydride annulus	2.59	1.60	1.16

[a]These are one-dimensional power ratios in the direction of solution and do not include the transverse effect.
[b]Scaled from value at 1673^{o} K.

TABLE IV. - CORE VARIATION

SPECIFICATIONS

Core	Diameter, cm	Length, cm	$\frac{\text{Length}}{\text{Diameter}} = \frac{L}{D}$
Basic	16.51	35.56	2.15
Squat	20.32	23.47	1.16
	25.40	15.01	.59
Split axial half-core	19.53	12.70	0.65
	21.84	10.16	.465
	23.34	8.89	.38

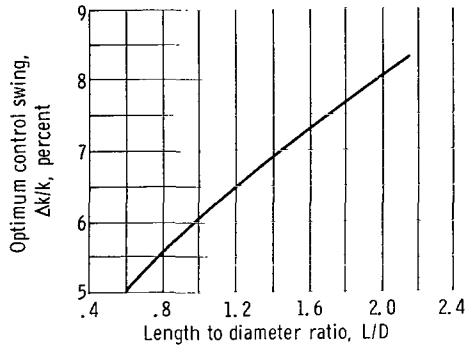


Figure 11. - Variation of optimum control swing with length to diameter ratio of core. Configuration: basic and squat cores; no pressure vessel; 10.16-centimeter yttrium hydride reflector.

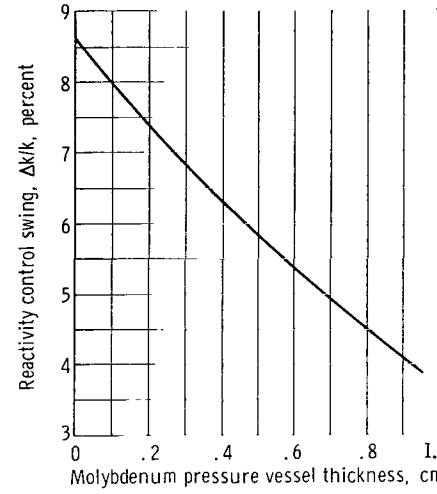


Figure 12. - Effect of molybdenum pressure vessel thickness on reactivity control swing.

control swing, as shown by the comparison of these squat cores to the basic core in figure 11.

Pressure vessel: Because temperature and pressure differences between the core and the reflector may reasonably be expected, a pressure vessel is necessary. Inclusion of a 0.9525-centimeter tantalum pressure vessel between the core and the YH_x region essentially erases the power peak (table III). Unfortunately the large tantalum resonances and thermal cross section also erase the control swing, which is dependent on thermal neutrons.

The effect of a molybdenum pressure vessel on the control swing as a function of pressure vessel thickness is shown in figure 12. The smaller thickness (0.40 cm) is an optimistic value based on minimum stress in the pressure vessel for a representative pressure of 6.89×10^5 newtons per square meter absolute (100 psia) and temperature of 1644° K. The larger value (0.9525 cm) is considered in the event greater pressures are encountered or material creep must be reduced. The $P_{max}/\overline{P}$ ratios are given in table III. An isotopic tungsten 184 pressure vessel, which has a thermal cross section and resonance integral comparable to that of molybdenum, should have about the same effect as molybdenum.

Shield: An estimate of the effect of an adjacent shield was determined by using a representative 7.62-centimeter lithium 6 hydride (Li^6H) shield outside the 10.16-centimeter YH_x region. This shield reduces the radial control swing by about a half percent. A Li^6H shield thickness of 50.80 centimeters reduces the radial control swing by about 0.2 percent. Greater shield thicknesses and different shield materials were not investigated because of their anticipated small effects on the control swing.

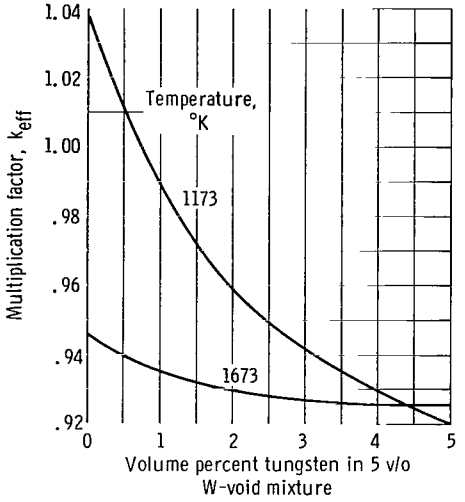


Figure 13. - Multiplication factor dependence on tungsten content in hydride reflector. Reflector, 95-volume-percent yttrium hydride - 5-volume-percent tungsten-void mixture.

Reflector support material: Since the fast-reactor core may operate at several hundred degrees above the reflector capability, some means of cooling the reflector may be needed. A high-temperature material will be needed to provide coolant passages as well as structural support for the reflector. For this purpose, tungsten was examined as a support material, although molybdenum could also be considered.

The volume percent of tungsten in a 95-volume-percent YH_x - 5-volume-percent tungsten-void mixture was varied. For comparison, a 0.05-centimeter-thick annulus of tungsten both inside and outside the YH_x annulus is about 1 volume percent of the combined YH_x and tungsten regions. Figure 13 shows the behavior of k_{eff} for reflector temperatures of 1173° and 1673° K as the void is replaced by tungsten. The initial addition of 0.13 volume percent tungsten in the reflector results in a loss of control swing of about 1 percent. The continual addition of tungsten into the void decreases the control swing until it is erased completely at a 4.3-volume-percent-tungsten - 0.7-volume-percent-void mixture. Adding more tungsten resulted in a positive reflector temperature coefficient.

For 5 volume percent tungsten, exclusion of the tungsten inelastic cross sections caused a nominal decrease in k_{eff}. Thus, it may be inferred that hydrogen is the dominant slowing down material and that tungsten in the reflector is neutronically important only as an absorber of neutrons.

Fuel seeded reflector. - There is a direct power coupling between the core and the reflector through prompt neutron and gamma heating in the reflector. The reactivity control of the hydride concept is dependent on the response time between a core temperature

change and the resulting change in hydrogen concentration in the reflector. However, it may be necessary to augment this direct power coupling to achieve desired temperature changes.

In order to sensitize the YH_x region temperature to the core behavior, seeding the YH_x region with small amounts of $U^{233}N$ was considered. The core fuel loading remained constant, while the total loading increased by the seeded amount of fuel. This power coupling of the YH_x region also substantially increases the control swing as well as the multiplication factor k_{eff}. For example, a reflector composition of 99.9-volume-percent YH_x - 0.1-volume-percent $U^{233}N$, with no pressure vessel, increases the control swing from 8.5 to 11 percent. For the 1173° K temperature, k_{eff} increases from 1.05 (without seeding) to 1.08 (with seeding). When this seeding concentration is used with the 0.9525-centimeter molybdenum pressure vessel, the control swing obtained is about 6 percent compared with about 4 percent without the coupling.

Figure 14 shows a nearly linear dependence of reactivity swing on small $U^{233}N$ seeding concentrations. A small seeding concentration of $U^{233}N$ could be chosen to give a desired control swing, in order to offset absorptive materials such as a pressure vessel or support structure. Increasing the control swing by this seeding process decreases the peak- to average-power ratio, as shown in figure 15, for three temperatures, 1173°, 1610°, and 1673° K.

It is desirable to limit the reflector power to about 10 percent of the total in order to limit the amount of power produced at the lower temperature which is possibly wasted. For this composition (0.1 v/o $U^{233}N$) the reflector power fraction varied from 3 percent

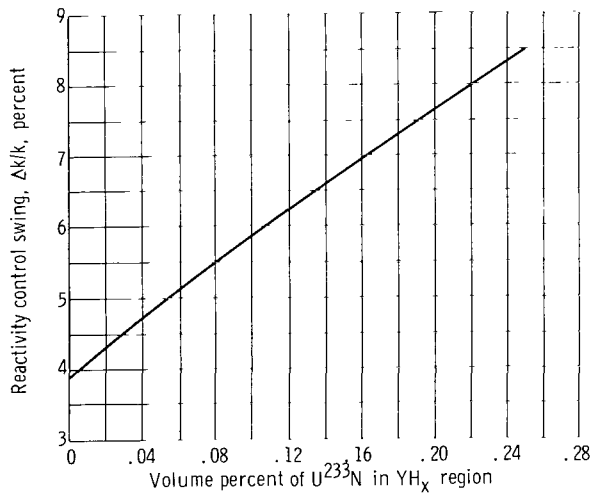


Figure 14. - Reactivity control swing at several $U^{233}N$ seeding concentrations. Configuration: basic core; molybdenum pressure vessel thickness, 0.9225 centimeter; seeded yttrium hydride reflector thickness, 10.16 centimeters.

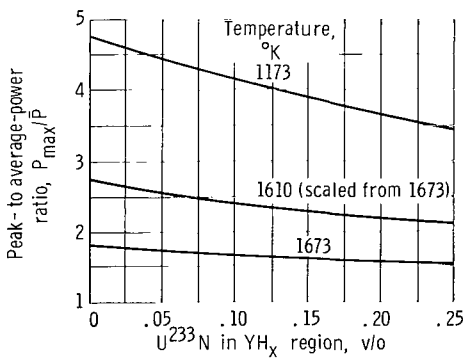


Figure 15. - Peak- to average-power ratio in core as function of $U^{233}N$ seeding concentration in yttrium hydride region. Molybdenum pressure vessel thickness, 0.9525 centimeter.

at an N_H of 1.375 (1673° K) to 12 percent at N_H = 5.5 (1173° K). At the beginning of reactor life, the high-temperature (low N_H) condition will exist and the 3-percent power fraction associated with it is quite acceptable. The fraction of 12 percent was computed with undepleted fuel at maximum hydrogen density, a condition which would not be achieved even at the end of the reactor life.

Depletion, which itself necessitates the higher N_H, will to some extent offset this increase in reflector power fraction. In fact, the relatively higher depletion in the reflector may also tend to lower this power fraction over the life of the reactor to the extent that the power fraction would not increase at all from the initial 3-percent value. Table V compares the reflector power fraction at the temperature extremes of 1173° and 1673° K for configurations with and without seeding and a pressure vessel.

TABLE V. - POWER FRACTIONS FOR FUEL SEEDED ANNULAR REFLECTOR

Composition, v/o		Power fraction	
YH_x	$U^{233}N$	1173° K	1673° K
With molybdenum pressure vessel (0.9525 cm)			
99.90	0.10	0.129	0.0334
99.75	.25	.269	.0734
Without pressure vessel			
99.90	0.10	0.126	0.0323

In summary, the cylindrical core with a 10.16-centimeter YH_x annular reflector offers a reactivity control swing of 8.5 percent. It is assumed that 2 percent swing is needed for shutdown and that another 1 percent will allow for the temperature defect. A molybdenum pressure vessel 0.4 centimeter thick costs 2 percent and a representative radiation shield costs another 0.5 percent in reactivity swing. If the control swing penalty of the support material in the reflector is assumed to be 1 percent, the total demand is for 6.5-percent reactivity swing. Seeding the YH_x reflector with 0.1 volume percent fuel provides 2.5 percent additional swing. The net swing thus available is 4.5 percent, which is sufficient for the supposed 4 percent burnup. However, removal of the power spike at the core-reflector interface would further reduce the control swing, and increasing the fuel seeding concentration above the 0.1-volume-percent level would be necessary

to offset this penalty. Thus, for this configuration, the fuel seeding is a necessary measure in order to obtain enough reactivity control.

Axial Configurations

A survey of cylindrical core-reflector configurations is not complete without consideration of the core with an axial reflector. The worth of an axial YH_x end reflector proved to be rather small in comparison with the worth of a radial reflector. The control swing from 1173° to 1673° K with a 10.16-centimeter YH_x top reflector and an 85 W bottom reflector is 0.7 percent.

A split axial configuration, consisting of a YH_x disk sandwiched between two cylindrical half-cores, placed the YH_x reflector in a region of greater neutronic importance (fig. 1(b)). The specifications of the core are given in table IV.

The results of independently varying the YH_x spacing thickness and the fuel thickness of the split axial reactor are shown in figure 16. The optimum YH_x spacing is shown to be about 5 centimeters. The optimum control swing for the split axial configuration is 8.0 percent compared with 8.5 percent for the radial configuration.

The depletion and cooling problems of the split axial configuration might be partly alleviated by orienting the fuel elements parallel to the cylinder axis. The axial power peaks (table III) will occur at only localized regions of some of the fuel elements. The gaseous fission products from high, localized burnup in an element could presumably

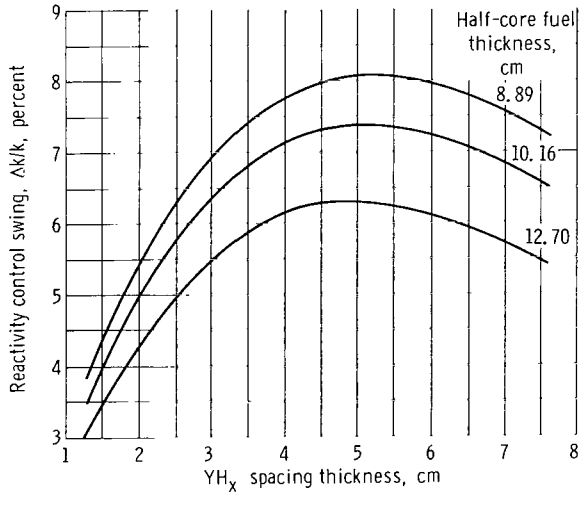


Figure 16. - Variation of reactivity control swing with yttrium hydride spacing thickness and with half-core fuel thickness as parameter. Configuration: split axial; no pressure vessel.

diffuse through a void space along the center of the element resulting in a lower average depletion rate, which may be tolerated.

The cooling of the axial power peaks would require a coolant inlet plenum in the central YH_x region with coolant flowing radially into the plenum then channeled axially to outlets at each end of the core. However, the size of this reactor would not permit such a coolant path. Thus, if conventional forced convective methods are to be used for cooling, the feasibility of this split axial configuration is at best marginal.

However, if a new and efficient method of high heat conductance, called a heat pipe (ref. 11), is used, the configuration becomes somewhat more promising. Use of axially oriented heat pipes would remove the need for a central plenum. Furthermore, the heat pipe, which tends to integrate power over its length, is an extremely simple device with no moving mechanical parts. Axial heat pipes have been previously considered in power generation systems with, for example, movable end reflector control (ref. 12).

Central Rod and Annular Reflector

Without fuel seeding the reflector in the annular configuration, only 8.5 percent reactivity control swing is available. However, 10.5 percent swing, which includes 4 percent burnup but does not include requirements for power tailoring, is needed.

The use of a central rod of YH_x in addition to an annular reflector exposes more of the fuel surface to the hydride moderator thereby increasing the control swing. A 0.4-centimeter molybdenum pressure vessel completely encloses the fuel annulus, and the

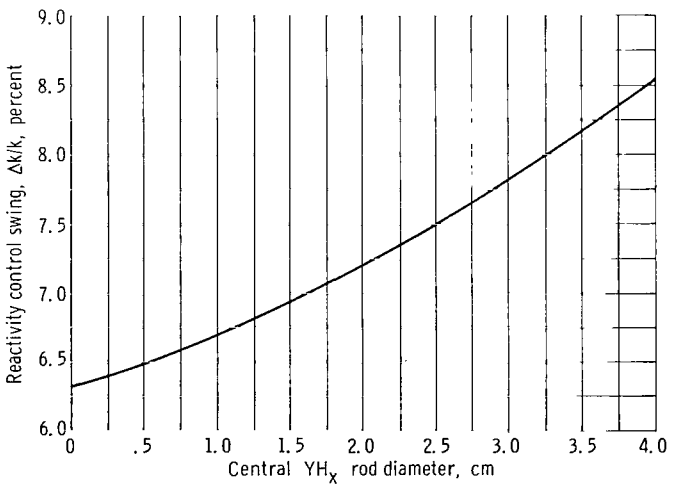


Figure 17. - Reactivity control swing dependence on central yttrium hydride rod diameter. Molybdenum pressure vessel thickness, 0.40 centimeter; yttrium hydride annular thickness, 10.16 centimeters.

annular hydride thickness remains at 10.16 centimeters.

Figure 17 shows the control swing as a function of central rod diameter which varies from 0 to 4 centimeters. Appendix B presents an extension to larger annular cores with large central YH_x regions. Reference to figure 17 indicates that a 4.0-centimeter-diameter central YH_x rod would provide an additional 2 percent reactivity control thus satisfying the 10.5 percent demand.

Actually, more than 10.5 percent $\Delta k/k$ is needed because of the power tailoring necessary to remove the power spikes. Power peaking occurs at both hydride-core interfaces (table III) but the outer spike (core-annulus interface) is more severe for the rod diameters considered.

Power Peak Reduction and Auxiliary Control Measures

A principal disadvantage of this reversible hydriding concept is the power peaking. Several methods for reducing the radial peak to a value of about 2.0 were considered. It is assumed that fuel zoning could accomplish any further required reduction in the peak.

The use of a burnable poison, such as boron 10 carbide ($B_4^{10}C$), in the vicinity of the power peak was examined. However, the poison tended to destroy the control swing and k_{eff} without any substantial decrease in the peak. Another approach is to reduce the peak at the core-YH_x annulus interface by decreasing the hydride annular thickness. Figure 18 and table III show the variation of P_{max}/P with YH_x annular thickness for both radial peaks. In each instance, the total annular reflector thickness is supplemented to 10.16 centimeters by molybdenum, since tungsten has been previously shown to be

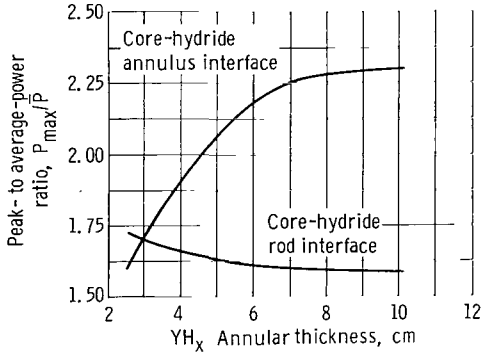


Figure 18. - Peak-to average-power ratio at operating temperature of 1610° K for 4.0-centimeter yttrium hydride rod configuration as function of yttrium hydride annular thickness. Two 0.40-centimeter-thick molybdenum pressure vessels are included.

quite deleterious. However, the sacrifice in control swing required to improve $P_{max}/\overline{P}$ by this means cannot be tolerated. To reduce the $P_{max}/\overline{P}$ of the outer radial peak to 2.0 costs 3.5 percent in control swing.

The behavior of $P_{max}/\overline{P}$ as a function of temperature is shown in figure 10. The hot critical operating point is indicated, and it may be seen that any decrease in hydrogen concentration (increase in YH_x temperature) is quite effective in lowering $P_{max}/\overline{P}$. The reactivity controlled by the temperature difference from 1673° to 1610° K is 3 percent (2 percent startup and 1 percent temperature defect).

If this reactivity burden of 3 percent can be borne by another means, such as a movable control rod, less hydride control would be demanded. The hot critical operating point could then occur at about 1673° K, and the power peak could be treated by fuel zoning. However, in order to allow adjustment of the reactivity control, it will be necessary to operate on the hydride curve (fig. 4) at a lower temperature (higher hydrogen concentration) than 1673° K. Thus, the power peak at the initial hot critical condition will be a little larger than that shown for 1673° K. The power profile with the YH_x at 1673° K is shown in figure 19.

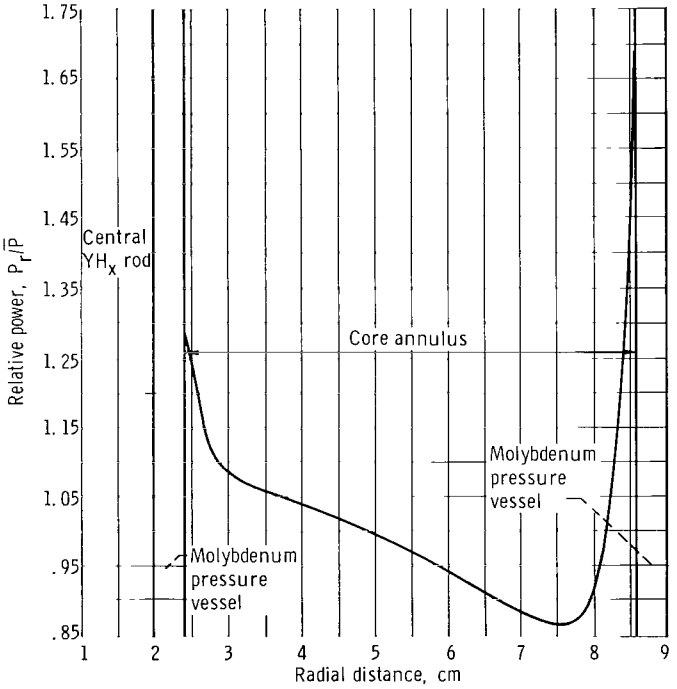


Figure 19. - Radial power distribution. Configuration: 4.0-centimeter central yttrium hydride rod; two 0.4-centimeter-thick molybdenum pressure vessels; 10.16-centimeter yttrium hydride annular reflector; yttrium hydride at 1673° K.

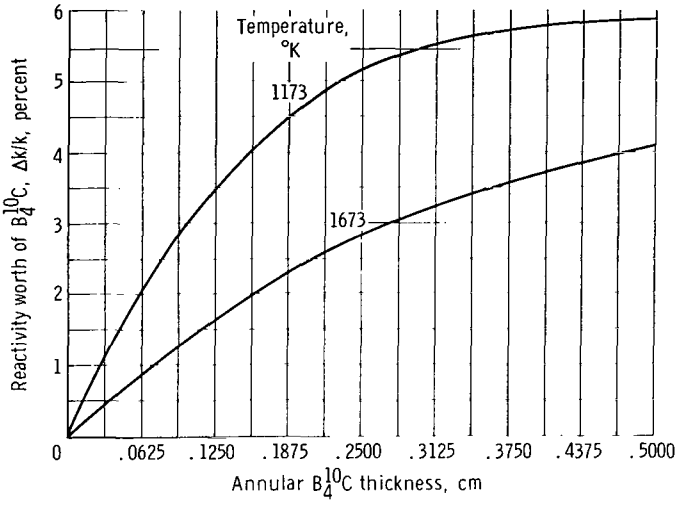
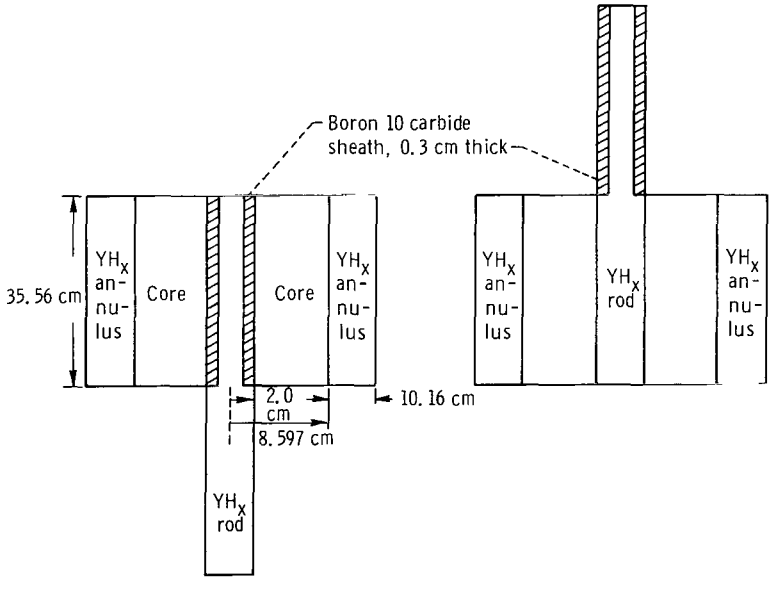


Figure 20. - Reactivity worth of boron 10 carbide sheath around central yttrium hydride rod as function of sheath thickness. Outer diameter of sheath maintained at 4.0 centimeters.



(a) Shutdown: sheath in core. (b) Operation: sheath out of core.

Figure 21. - Shutdown and operation configurations of central YH_x rod and boron 10 carbide control sheath.

The worth of a $B_4^{10}C$ sheath, displacing YH_x, around the central YH_x rod is shown in figure 20. A sheath thickness of about 0.30 centimeter would provide about 3 percent reactivity control at 1673° K. The $B_4^{10}C$ annulus supplements the hydride rod to a diameter of 4.0 centimeters. The reflector configuration showing $B_4^{10}C$ sheathed and unsheathed portions of the control rod in prestartup or shutdown and in operating position is shown in figure 21.

The use of the $B_4^{10}C$ sheathed and unsheathed YH_x rod provides the 3 percent reactivity swing needed to achieve the hot critical condition. The full reactivity swing (8.5 percent) between hydride temperatures of 1673° and 1173° K, with a 4.0-centimeter YH_x rod and a 10.16-centimeter YH_x annulus, is still available. Additional assumed reactivity penalties are 1 percent for hydride support and 0.5 percent for shielding, leaving 4 percent for burnup and 3 percent for power tailoring.

CONCLUSIONS

The use of a reversibly hydrided yttrium hydride zone as a reactivity control method for a fast-spectrum nuclear reactor has been studied. A fourfold variation of the equilibrium hydrogen concentration in yttrium hydride appears sufficient to provide the reactivity changes needed for most of the required control of a fast-spectrum reactor. Since the control swing provided by the yttrium hydride reflector is dependent on thermal neutrons, parasitic thermal absorption must be minimized. Seeding the yttrium hydride with nuclear fuel can provide additional reactivity control swing.

For a cylindrical core with a simple annular reflector (10.16-cm yttrium hydride) about 8.5 percent reactivity control swing is available although at least 10.5 percent swing is needed. Furthermore, power tailoring will be necessary to remove power peaks with a peak to average ratio of about 4.0 and this tailoring will reduce the available control swing. It is then necessary to seed the hydride reflector with fuel to provide the additional control swing.

The split axial configuration, consisting of an yttrium hydride disk between two cylindrical half-cores, did not have sufficient control swing to meet the requirements of a conventional convective cooling approach. However, the configuration shows more promise if used with a heat pipe cooling system.

An annular core configuration with the hydride moderator as a central rod and as an exterior annulus exposes more fuel surface to the hydride and thereby provides substantially more control swing. With a 4.0-centimeter-diameter central yttrium hydride rod and a 10.16-centimeter yttrium hydride annulus, a control swing of 10.5 percent is obtained. However, the peak- to average-power ratio is still about 2.3.

It appears that power peaking is so severe that auxiliary control measures may be necessary. Of several methods considered for reducing the power peak, a promising approach is to use a movable thermal poison sheath around the central yttrium hydride rod. This sheath can be chosen to provide the startup and temperature defect reactivity margins. A 0.30-centimeter-thick boron 10 carbide annular sheath supplementing a central yttrium hydride rod to a diameter of 4.0 centimeters is worth 3 percent in reactivity control. This lessens the control demand on the hydride and allows a lower initial hydrogen concentration (higher temperature). The initial power spike is thus much less, and it is assumed that fuel zoning can further tailor the power to an acceptable profile. Reactivity control of about 8.5 percent, entirely from the temperature variation of the hydride, is available. Allowing 4 percent for burnup and 1.5 percent for canning and shielding leaves 3 percent for power tailoring.

The self-regulating property obtainable from temperature dependent reversible hydriding of yttrium zones is an attractive feature of this control concept.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, February 15, 1968,
120-27-06-18-22.

APPENDIX A

CHARACTERISTICS OF METAL HYDRIDES

The metal hydrides of titanium, zirconium, and yttrium appear useful for space nuclear power systems. Because of their large hydrogen content (comparable to that of water), their shielding qualities are desirable. And because of the large reversible variation of the equilibrium hydrogen content with temperature, these hydrides may be considered as possible reactivity control materials.

Because they contain moderately heavy metals, these hydrides (1) are more effective as gamma shielding materials than water and organic materials, (2) are metallic and may be fabricated, and (3) tend to be self-supporting structures at elevated temperatures ($>773^{\circ}$ K), but would probably require cladding in event of cracking.

A more detailed review of the properties of each of these metal hydrides is now given. This review is taken mainly from reference 1. Comparison of various metal hydride characteristics is given in figure 2 and table VI.

Titanium Hydride

Titanium hydride has a higher useful hydrogen content per unit volume than any known thermally stable (above 473° K) massive solid material, including organic hydrocarbons. Its hydrogen density is 0.16 gram of hydrogen per cubic centimeter compared with 0.111 gram of hydrogen per cubic centimeter for water at standard conditions. This hydride has a relatively low density of about 3.8 grams per cubic centimeter. The thermal absorption cross section of titanium, 5.8 barns, is somewhat high.

Fine grain structures have been hydrided to high N_H values of 8.0 to 8.5 atoms per barn-meter. More massive titanium hydride bodies (14.0 kg) have been hydrided to $N_H = 7.2$. For comparison, water at standard temperature and pressure has an N_H of about 6.7. Above 873° K, the N_H of titanium hydride drops rapidly with temperature.

After heating hydrided titanium for 2500 hours at 813° K in static furnace air, specimens showed a nominal average weight gain of 0.145 percent and thus considerable thermal stability.

Titanium hydride samples, containing 2 weight percent hydrogen, have thus demonstrated (1) outstanding strength and ductility at temperatures above 623° K, and (2) retention of useful engineering properties after prolonged exposure under normal atmospheric conditions.

TABLE VI. - HYDROGENOUS MATERIAL CHARACTERISTICS[a]

Material	Density, g/cm^3	Temperature of density measurements, ^oK	Hydrogen, w/o	Hydrogen density, N_H, atoms/b-m	Melting point, ^oK	Thermal absorption cross section,[b] b	Temperature dependent range,[c] ^oK	Remarks
Titanium hydride (TiH_x: x = 0 to 2)	4.5 to 3.8	300	0 to 3.9	0 to 9.0	------	5.8	800 to 1300	Self-supporting; needs no surface protection in air
Zirconium hydride (ZrH_x: x = 0 to 2)	6.5 to 5.62	300	0 to 2.1	0 to 6.7	------	0.18	925 to 1600	Self-supporting; needs no surface protection in air
Yttrium hydride (YH_x: $x \approx 2$)	4.3	300	2.0 to 2.1	5 to 5.3	------	1.38	1173 to 1673	Self-supporting; normally requires surface protection in air
Calcium hydride (CaH_x)	1.6 to 2.0	300	0 to 5.4	0 to 5.4	1089	0.43	----------	Normally requires surface protection at all temperatures
Lithium hydride (LiH)	0.75 to 0.78	300	12.6	[d]5.9	956.5	71.0	----------	Normally requires surface protection in air; requires containment and structural support
	[d]0.55	973	----------	4.1	------	--------	----------	----------
Water (H_2O)	0.917	273	11.1	6.1	273	0.00002	----------	----------
	1.0	277	----------	[e]6.7	------	.00002	----------	Requires containment and structural support
Yttrium (Y)	4.472	---	0	0	1782	1.38	----------	Self-supporting; needs no surface protection in air

[a]Data taken from ref. 1, with the exception of cross section, temperature dependent range, and the material yttrium.
[b]Of nonhydrogenous constituent.
[c]Approximate range in which the hydrogen concentration is temperature dependent.
[d]Liquid phase.
[e]273° K.

Zirconium Hydride

Zirconium hydride seems to be the most exploited of the three hydrides for nuclear reactor purposes (refs. 1 and 4). The reason for this greater exploitation may be attributed mainly to its low thermal absorption cross section of 0.18 barn. The density of zirconium hydride is about 5.6 grams per cubic centimeter, and N_H values of 6.0 appear practical for engineering applications. Above 1073° K, N_H drops sharply to about 1.0 at 1573° K. Samples in air at 923° K have retained their dimensional stability and more than 95 percent of their hydrogen over time periods greater than 1000 hours.

Yttrium Hydride

Yttrium hydride offers the most promise for fast reactors principally because it has an almost 200° K higher temperature capability than the other hydrides. Specifically, lower equilibrium hydrogen pressures result because its absorbed hydrogen content is greater than that for the other hydrides. This hydride (YH_x) has a density of 4.3 grams per cubic centimeter at room temperature where the stoichiometric ratio x is approximately 2. This density corresponds to $N_H = 5.5$ and $N_Y = 2.75$. The thermal absorption cross section of yttrium is about 1.3 barns.

An extrapolation of data in reference 1 (see fig. 2) will yield a fourfold reduction in N_H (5.5 at 1173° K to 1.375 at about 1673° K). The limitation to a fourfold reduction is chosen in view of the pressure limitation in figure 3 which indicates x has a lower limit of 0.5 at conveniently attainable low pressures.

This hydride normally needs surface protection in air. Several specimens of 95 volume percent yttrium - 5 volume percent chromium alloy, hydrided to $N_H = 5.1$ to 5.3 (about 2 w/o hydrogen), clad with 0.04 centimeter of iron-chromium-aluminum alloy were subjected to thermal stability tests. After 5000 hours in air at 1223° K, no cracks were apparent. The cracking that occurred before 10 000 hours had no measurable effect on dimensional stability. Destructive analysis after 10 000 hours at 1223° K showed that greater than 90 percent of the original hydrogen remained.

A similar specimen was exposed in air at 1173° K to an estimated thermal neutron exposure of 1.3×10^{20} nvt over 5100 hours. Little or no evidence of distortion or dimensional or weight instability was found. Ultrasonic inspection showed the clad-to-core bonding to be intact.

APPENDIX B

LARGE ANNULAR CORES

The introduction of an yttrium hydride central rod into the reactor core substantially increases the control swing over that available with only a hydride annulus. This increase occurs because more fuel surface area is exposed to the thermalizing hydride area. It is thus of interest to increase this exposed fuel surface area further and observe the control swing. In addition, if the central rod can be made large enough, a coolant cycle which starts in the central region and flows radially outward can be considered. This would enable optimum heat transference to the coolant in the vicinity of the interior power spike and thus might negate the deleterious effects of the spike.

The following equation shows the dependence of the surface to volume ratio S/V on the annular parameters (for a constant volume):

$$V = \pi\left(R_O^2 - R_I^2\right)L$$

$$\frac{S}{V} = 2\left[\frac{1}{L} + \frac{1}{(R_O - R_I)}\right]$$

The inside and outside radii are R_I and R_O, respectively; the length is L. It is readily seen that by decreasing the thickness of the fuel annulus $(R_O - R_I)$ and increasing R_O and R_I to conserve volume, larger cores result.

The reactor examined contains 0.0623 cubic meter of fuel matrix: 28.2 volume percent uranium 233 dioxide, 24.4 volume percent void, 22.2 volume percent lithium 7 coolant, and 25.2 volume percent molybdenum clad. The central hole diameter varies from 15.24 to 30.48 centimeters; at 30.48 centimeters, the fuel annular thickness is 11.056 centimeters. The YH_x density in the hole varies from 24 to 49 volume percent of the full density. A 0.635-centimeter-molybdenum pressure vessel is used inside and outside the fuel region and a 10.16-centimeter YH_x reflector surrounds the fuel annulus. The length of the reactor is 43.18 centimeters.

Figure 22 shows the control swing as a function of the central hole or rod diameter. Figure 23 shows the control swing as a function of hydride density in a 30.48-centimeter hole. This figure indicates that, as the YH_x density increases, the thermal absorption in yttrium causes decoupling of the reactor.

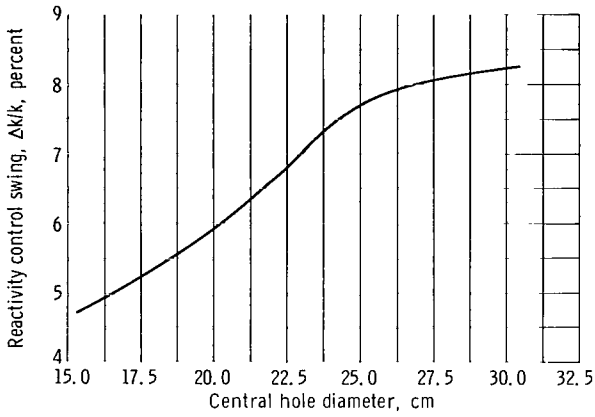


Figure 22. - Reactivity control swing as function of large central hole or rod diameter. Yttrium hydride in central hole, 34 percent; annular core thickness varies to conserve fuel volume; core height, 43.18 centimeters.

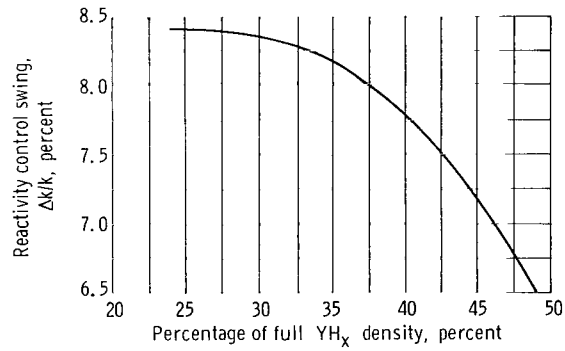


Figure 23. - Reactivity control swing as function of yttrium hydride density in central hole 30.48 centimeters in diameter. Annular core thickness, 11.056 centimeters; core height, 43.18 centimeters.

REFERENCES

1. Van Houten, Robert; and Baxter, W. G.: Titanium, Zirconium, and Yttrium Hydrides as Space Shielding Materials. J. Spacecraft Rockets, vol. 2, no. 3, May-June 1965, pp. 469-472.

2. Rosenthal, H. B.; Szymkowiak, E. A.; and George, C. H.: Hydrogen Reactivity Control Experiment: Performance and Results. Trans. Am. Nucl. Soc., vol. 10, no. 1, June 1967, p. 366.

3. Hooks, Kenneth R.: Feasibility Study of Terrestrial Thermoelectric Nuclear Power Plant. Martin Co. (AFWL-TR-66-16, DDC No. AD-486713), June 1966.

4. Zindler, G. F.: Terrestrial Direct Conversion Nuclear Power Plant Conceptual Design. Rep. No. MND-3193 (AFWL-TR-64-168, DDC No. AD-460642), Martin Co., Mar. 1965.

5. Magladry, Robert: Hydrogen Diffusion Reactor Control. Patent No. 3, 351, 534, United States, Nov. 7, 1967.

6. Lundin, C. E.; and Blackledge, J. P.: Pressure-Temperature-Composition Relationships of the Yttrium-Hydrogen System. J. Electrochem. Soc., vol. 109, no. 9, Sept. 1962, pp. 838-842.

7. Anderson, John L., Jr.: VULCAN-A Depletion Program for Use with Independent One-Dimensional Spatial Calculations. NASA TN D-4151, 1967.

8. Joanou, G. D.; and Dudek, J. S.: GAM-II. A B_3 Code for the Calculation of Fast-Neutron Spectra and Associated Multigroup Constants. Rep. No. GA-4265, General Dynamics Corp., Sept. 16, 1963.

9. Joanou, G. D.; Smith, C. V.; and Vieweg, H. A.: GATHER-II - An IBM-7090 FORTRAN-II Program for the Computation of Thermal-Neutron Spectra and Associated Multigroup Cross Sections. Rep. No. GA-4132, General Dynamics Corp., July 8, 1963.

10. Barber, Clayton E.: A FORTRAN IV Two-Dimensional Discrete Angular Segmentation Transport Program. NASA TN D-3573, 1966.

11. Feldman, K. T., Jr.; and Whiting, G. H.: The Heat Pipe. Mech. Eng., vol. 89, no. 2, Feb. 1967, pp. 30-33.

12. Barnett, C. S.: An Out-of-Pile Heat Pipe Thermionic Space-Power Concept. Trans. Am. Nucl. Soc., vol. 9, no. 2, Nov. 1966, pp. 338-339.

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